Mon. Not. R. Astron. Soc. **351,** 292–296 (2004) doi:10.1111/j.1365-2966.2004.07781.x

Ultraviolet/optical emission accompanying gamma-ray bursts

Y. Z. Fan[1,2★] and D. M. Wei[1,2★]

[1] *Purple Mountain Observatory, Chinese Academy of Science, Nanjing 210008, China*
[2] *National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China*

Accepted 2004 February 27. Received 2004 February 26; in original form 2003 September 28

ABSTRACT

We discuss the possible simultaneously ultraviolet (UV)/optical emission accompanying gamma-ray bursts (GRBs). We show that as long as the intrinsic spectrum of GRBs can extend to $\sim$10 GeV or higher, there are large amounts of relativistic $e^{\pm}$ pairs generated due to the annihilation of soft gamma-rays with very energetic photons, which dominates over the electrons/positrons associated with the fireball, whether the fireball is highly magnetized or not (for the highly magnetized fireball, the magnetic field is ordered, high linear polarization of multiwavelength emission is expected). We find that these $e^{\pm}$ pairs can power a UV flash with $m \simeq 12$–13 mag, and the corresponding optical emission can be up to $m_R \simeq 15$–16 mag. Such bright UV emission will be able to be detected by the satellite *Swift*, planned for launch in 2004. The behaviour of the optical–UV spectrum ($F_\nu \propto \nu^{5/2}$) differs significantly from that of the reverse shock emission ($F_\nu \propto \nu^{-\beta/2}$, $\beta \simeq 2.2$), which is a signature of the emission accompanying the GRB. Mild optical emission can be detected with the ROTSE-IIIa telescope system, if the response to the GRB alert is fast enough.

Key words: radiation mechanisms: non-thermal – gamma-rays: bursts.

1 INTRODUCTION

Although the central engine for gamma-ray bursts (GRBs) is far from clear, it is generally suggested that gamma-ray bursts are powered by the dissipation of energy in a highly relativistic wind, driven by the gravitational collapse of a massive star into a neutron star or a black hole (see Cheng & Lu 2001; Mészáros 2002 for recent reviews). There are two possible models involving this scenario: one is the internal shocks model (Paczyński & Xu 1994; Rees & Mészáros 1994) involving a baryon-rich fireball, which can reproduce the observed temporal structure in GRBs naturally. The other is the Poynting flux driven outflows from magnetized rotators (Thompson 1994; Usov 1994; Mészáros & Rees 1997). Comparing with the widely accepted baryon-rich fireball model, the Poynting flux model is of increasing interest, since: (i) it provides us with the most plausible explanation for the very high linear polarization during the prompt gamma-ray emission of GRB 021206 (e.g. Coburn & Boggs 2003; Lyutikov, Pariev & Blndford 2003), although some alternative explanations still remain (e.g. Shaviv & Dar 1995; Waxman 2003). (ii) Modelling the reverse shock emission of GRB 990123 indicates that the reverse shock region should anchor a strong field far more than the forward shock region does (Fan et al. 2002; Zhang, Kobayashi & Mészáros 2003), which hints that the fireball may be highly magnetized (see the review of Zhang & Mészáros 2003 for more detail).

In the afterglow epoch, little theoretical attention has been paid to the emission at ultraviolet (UV)/optical emission during the gamma-ray burst phase. Pilla & Loeb (1998) have discussed such emission in the internal shocks. However, in their work, the synchrotron self-absorption effect has been ignored (see their fig. 3, the spectrum at the optical–UV band takes the form of $F_\nu \propto \nu^{1/3}$). Conversely, before the discovery of the afterglow, this topic was of some interest (e.g. Katz 1994; Schaefer et al. 1994; Wei & Cheng 1997). In this paper, we reinvestigate that topic in some detail. In contrast to previous works, we emphasize the contribution of the $e^{\pm}$ pairs generated in the phase of γ burst – as long as the intrinsic spectrum can extend to $\sim$10 GeV or higher, there are large amounts of relativistic $e^{\pm}$ pairs generated due to the annihilation of the soft gamma-rays with energetic photons with energy up to 10 GeV, just as realized by several authors previously (e.g. Pilla & Loeb 1998; Guetta, Spada & Waxman 2001; Mészáros et al. 2002; Li et al. 2003; Fan, Dai & Lu 2004a).[1] There is some evidence that the spectra of some GRBs extend to >100 MeV (e.g. Schaefer et al. 1998; González et al. 2003; Guetta & Granot 2003). For some GRBs observed by EGRET, a significant fraction of power has been emitted into the GeV energy range, and the spectra can be described by a single power law ranging from the MeV to the GeV energy band (see Fishman & Meegan 1995 for a review). We find that those resulting $e^{\pm}$ pairs power a bright UV flash with $m \simeq 12$–13 mag, the corresponding optical

★E-mail: yzfan@pmo.ac.cn (YZF); dmwei@pmo.ac.cn (DMW)

[1] During the revision of our paper, a very detailed numerical calculation appeared (Pe'er & Waxman 2003).

emission can be up to $m_R \simeq 15$–16 mag. Such bright UV emission can be detected by the Satellite *Swift*, planned for launch in 2004. The mild optical emission can be detected with the ROTSE-IIIa telescope system, if the response to the GRB alert is fast enough.

This paper is structured as follows: in Section 2, we discuss pair production and the possibility of annihilation in the gamma-ray burst phase. In Section 3, we calculate the synchrotron radiation of these new born relativistic $e^{\pm}$ pairs. Conclusions and discussions on the observations are given in Section 4.

2 PAIR LOADING IN GRBS

History, a large Lorentz factor $\eta \sim 100$–1000 is first introduced to avoid the 'compactness problem' in GRBs. However, a significant fraction of photons with very energetic energy may still suffer from absorption and hence yield considerable amounts of $e^{\pm}$ pairs. Pilla & Loeb (1998) have studied the spectral signatures of the GRB itself by considering pair production and have shown there are large amounts of $e^{\pm}$ pairs generated. The comoving annihilation time of these pairs is longer than the hydrodynamical time, so they can survive in the wind for a long time. For this reason, Li et al. (2003) have reinvestigated the pair generation in the gamma-ray burst phase and studied the reverse shock emission powered by a such pair-rich fireball interacting with the interstellar medium (ISM), and shown that this results in very strong infrared flashes. In those two works, the resulting pairs dominate over the electrons associated with baryons. Generally, the typical thermal Lorentz factor of these resulting $e^{\pm}$ pairs is only several tens, its synchrotron radiation contributes little to the gamma-ray band. Consequently, only its inverse Compton (IC) radiation has been calculated (Pilla & Loeb 1998; Fan et al. 2004a). In this paper we turn to investigate the emission at a much lower energy band, i.e. the UV/optical band.

As mentioned earlier, for the most energetic photons at the high energy end of the spectrum, the optical depth of γ–γ absorption may exceed unity. As a result, rather than escaping from the outflow, these photons are absorbed by the soft gamma-rays and hence yield relativistic $e^{\pm}$ pairs. Below, following Li et al. (2003) and Fan et al. (2004a), we calculate how many pairs are generated in this process for a pulse with a typical variable time-scale $\delta t \sim 0.1$ s (Shen & Song 2003).

An excellent phenomenological fit for the GRB spectrum was introduced by Band et al. (1993), which is characterized by two power laws joined smoothly at a break frequency $\nu_{\rm b} \approx 1.21 \times 10^{20}$ Hz. For $\nu > \nu_{\rm b}$, the photon spectra can be approximated by a power law $dN/d\nu = N_{\nu_{\rm b}}(\nu/\nu_{\rm b})^{-(p+2)/2}$, where $N_{\nu_{\rm b}} = (p-2)(h\nu_{\rm b}^2)^{-1}L\,\delta t/2(p-1)$ (Dai & Lu 2002), $p \simeq 2.5$ is the index for a power-law distribution of relativistic electrons/positrons accounting for the observed gamma-ray emission. Therefore, for $\nu > \nu_{\rm b}$ we have

$$N_{>\nu} = \int_{\nu}^{\infty} (dN/d\nu)\,d\nu$$
$$= [(p-2)/p(p-1)](h\nu_{\rm b})^{-1}(\nu/\nu_{\rm b})^{-p/2}L\,\delta t. \qquad (1)$$

A photon with energy $h\nu$ may annihilate any photons above the energy $h\nu_{\rm an} = (\eta m_{\rm e}c^2)^2/h\nu$, the optical depth is given by (Lithwick & Sari 2001; Dai & Lu 2002; Li et al. 2003)

$$\tau_{\gamma\gamma}(\nu) = \frac{(11/180)\sigma_{\rm T}N_{>\nu_{\rm an}}}{4\pi(\eta^2 c\,\delta t)^2}. \qquad (2)$$

A photon with $\tau_{\gamma\gamma}(\nu) > 1$ would be absorbed and then deposited in the fireball. The condition $\tau_{\gamma\gamma}(\nu) = 1$ results in $\nu_{\rm an} \approx 6.4 \times 10^{20}$ Hz $\nu_{\rm b,20.1}^{(p-2)/p}L_{52}^{2/p}\,\delta t_{-1}^{-2/p}\eta_{2.5}^{-8/p}$ (in this paper, we adopt the convention $Q_x = Q/10^x$ to express the physical parameters, using cgs units). The cut-off frequency is

$$\nu_{\rm cut} = 2.2 \times 10^{24}\ {\rm Hz}\ \nu_{\rm b,20.1}^{(2-p)/p}L_{52}^{-2/p}\,\delta t_{-1}^{2/p}\eta_{2.5}^{(2p+8)/p}, \qquad (3)$$

the corresponding 'thermal' Lorentz factor of resulting $e^{\pm}$ pairs reads

$$\gamma_{\rm pair,m} \approx \frac{h\nu_{\rm cut}}{2\eta m_{\rm e}c^2} = 29\nu_{\rm b,20.1}^{(2-p)/p}L_{52}^{-2/p}\,\delta t_{-1}^{2/p}\eta_{2.5}^{(p+8)/p}. \qquad (4)$$

The total number of the resulting $e^{\pm}$ pairs is

$$N_{e^{\pm}} = [(p-2)/p(p-1)](h\nu_{\rm b})^{-1}(\nu_{\rm cut}/\nu_{\rm b})^{-p/2}L\,\delta t$$
$$= 7.4 \times 10^{50}L_{52}^2\eta_{2.5}^{-(p+4)}\nu_{\rm b,20.1}^{p-2}. \qquad (5)$$

In principle, a more detailed numerical calculation is needed to calculate the number of generating $e^{\pm}$ pairs just as Pilla & Loeb (1998) and Guetta et al. (2001) have done. However, here we will show that our analytical estimation (equation 5) coincides with the numerical results of Pilla & Loeb (1998) quite well. For the numerical example holding in Pilla & Loeb (1998): $E \approx 10^{51}$ erg, $M \approx 10^{27}$ g, $\delta t \approx 0.01$ s and $\eta \approx 400$ (where M is the mass of the shell, and other parameters have the usual meanings). With these values, our equation (5) reads $N'_{e^{\pm}} \approx 1.14 \times 10^{52}L_{53}^2\eta_{2.6}^{-(p+4)}\nu_{\rm b,20.1}^{p-2}$. On the other hand, the number of the electron associated with baryons $N'_{\rm e} = M/m_p \approx 6.0 \times 10^{50}$. The ratio of them is $2N'_{e^{\pm}}/N'_{\rm e} \approx 38$. Please note that in the original work of Pilla & Loeb (1998) they obtain a ratio of approximately 40! Such an excellent coincidence implies that our analytical treatment is reasonable and that our results are reliable.

These resulting $e^{\pm}$ pairs may annihilate each other into gamma-rays again. This possibility has been discussed in great detail by Pilla & Loeb (1998), Li et al. (2003) and Fan et al. (2004a). For typical GRB parameters, $\eta \sim 300$, $\delta t \sim 0.1$ s, $L \sim 10^{52}$ erg s^{-1}, the annihilation time of these pairs is much longer than the hydrodynamic time (measured in the comoving frame). As a result, these new born $e^{\pm}$ pairs survive in the wind for a long time rather than annihilate locally, this is the only case for which our following calculations are valid.

3 SYNCHROTRON EMISSION AT THE UV/OPTICAL BAND

The resulting $e^{\pm}$ pairs are in a fast cooling phase, most of them cool down to $\gamma_{\rm e} \sim 1$ rapidly. However, it is well known that only the emission of the relativistic electrons/positrons can be described by the synchrotron radiation. For the subrelativistic electrons, their cyclotron radiation contributes little to the UV/optical emission that is of interest to us. Therefore, in this paper, only the electrons with the Lorentz factor $\gamma_{\rm e} > \gamma_{\rm e,c}$ ($\gamma_{\rm e,c}$ represents a critical Lorentz factor, which performs the same role as the 'cooling Lorentz factor' elsewhere) have been taken into account. As an illustration, we take $\gamma_{\rm e,c} = 2$. In the following discussion, the superscripts 'm' and 'b' represent the highly magnetized fireball and baryon-rich fireball, respectively.

3.1 Baryon-rich fireball

For a baryon-rich fireball, the total number of the electrons accounting for the observed gamma-ray emission can be estimated by $N_{\rm e,tot}\eta\gamma_{\rm m}m_{\rm e}c^2 = E_\gamma$, $\gamma_{\rm m}$ is the typical Lorentz factor of electrons, which is constrained by $\eta\gamma_{\rm m}^2 eB^{\rm b}/2\pi m_{\rm e}c = \nu_{\rm b}$. $B^{\rm b}$ is the strength of the comoving magnetic field, which can be estimated as follows: assuming $E_{\rm B} = \epsilon_{\rm B}E_\gamma$ (where $E_{\rm B}$ is the total magnetic energy carried by the fireball and E_γ is the total energy emitted in the gamma-ray band), we have $4\pi(\eta^2 c\delta t)^2\, c(B^{b2}/8\pi)\eta^2 = \epsilon_B L$, which leads to $B^b = 2.9\times10^3$ Guass $L_{52}^{1/2}\eta_{2.5}^{-3}\,\delta t_{-1}^{-1}\epsilon_{B,-1}^{1/2}$. After some simple algebra we have

$$N_{e,tot} = 5.8\times10^{52}E_{\gamma,53}L_{52}^{1/4}\eta_{2.5}^{-2}\,\delta t_{-1}^{-1/2}\epsilon_{B,-1}^{1/4}\nu_{b,20.1}^{-1/2}. \tag{6}$$

For a typical pulse with a typical variable time-scale of δt, the electrons contained can be estimated as

$$N_e = N_{e,tot}\,\delta t/T = 5.8\times10^{50}L_{52}^{5/4}\eta_{2.5}^{-2}\,\delta t_{-1}^{1/2}\epsilon_{B,-1}^{1/4}\nu_{b,20.1}^{-1/2}, \tag{7}$$

where $T\sim 10$ s (measured in the local frame) is the typical 'effective' duration of GRBs, within which the light curve is relatively smooth and most of the total energy has been emitted. Thus $L\approx E_\gamma/T$. Now we can define a coefficient $k_\pm$ as

$$k_\pm \equiv N_{e^\pm}/N_e = 1.3L_{52}^{3/4}\eta_{2.5}^{-(p+2)}\nu_{b,20.1}^{p-3/2}\,\delta t_{-1}^{-1/2}\epsilon_{B,-1}^{-1/4}. \tag{8}$$

With equation (4), the characteristic synchrotron emission frequency of the new born $e^\pm$ can be estimated by

$$\begin{aligned}\nu_m^b &= \eta\gamma_{pair,m}^2\frac{eB^b}{2\pi m_e c}\\ &\approx 2.0\times10^{15}\,\mathrm{Hz}\,\epsilon_{B,-1}^{1/2}\nu_{b,20.1}^{2(2-p)/p}L_{52}^{(p-8)/2p}\,\delta t_{-1}^{(4-p)/p}\eta_{2.5}^{16/p},\end{aligned} \tag{9}$$

where m_e is the mass of the electron.

An electron with a Lorentz factor γ_e ($\gg\gamma_{e,c}$) cools down to $\gamma_{e,c}$ at a time-scale

$$t_{life}^b \approx 3\pi m_e c/\sigma_T B^{b^2}\eta\gamma_{e,c} \approx 0.076\,\mathrm{s}\,\epsilon_{B,-1}^{-1}L_{52}^{-1}\eta_{2.5}^5\,\delta t_{-1}^2. \tag{10}$$

which is comparable with δt. The characteristic frequency with respect to $\gamma_{e,c}$ is

$$\nu_c^b = \eta\gamma_{e,c}^2\frac{eB^b}{2\pi m_e c} \approx 9.8\times10^{12}\,\mathrm{Hz}\,\epsilon_{B,-1}^{1/2}L_{52}^{1/2}\eta_{2.5}^{-2}\,\delta t_{-1}^{-1}. \tag{11}$$

To calculate the observed energy flux, the synchrotron self-absorption effect must be considered. Now, the electrons/positrons can be classified into two components: the first is that the electrons account for the gamma-ray emission with a distribution of $dn/d\gamma_e \propto \gamma_e^{-2}$ for $\gamma_{e,c} < \gamma_e < \gamma_m$ and $dn/d\gamma_e \propto \gamma_e^{-(p+1)}$ for $\gamma_e > \gamma_m$. The other is the resulting $e^\pm$ pairs with the distribution $dn/d\gamma_e \propto \gamma_e^{-2}$ for $\gamma_{e,c} < \gamma_e < \gamma_{pair,m}$ and $dn/d\gamma_e \propto \gamma_e^{-(p+4)/2}$ for $\gamma_e > \gamma_{pair,m}$. For the former, the synchrotron self-absorption frequency can be estimated by (see the appendix of Wu et al. 2003 for detail): $\nu_a = 2.4\times10^{15}$ Hz $L_{52}^{3/4}\eta_{2.5}^{-3}\,\delta t_{-1}^{-7/6}\epsilon_{B,-1}^{5/12}\nu_{b,20.1}^{-1/6}$. For the latter, the synchrotron self-absorption frequency can be estimated by (Wu et al. 2003): $\nu_a' = 4.0\times10^{15}$ Hz $[\epsilon_{B,-1}^{p/2}\eta_{2.5}^{-4(p+2)}\ \delta t_{-1}^{-(p+8)}L_{52}^{(8+p)/2}\nu_{b,20.1}^{2(p-2)}]^{1/(p+12)}$. In practice, the self-absorption frequency of such a system is determined by these two components jointly rather than separately. Here, as a rough estimation, we assume the actual self-absorption frequency is approximately k [$\simeq 1 + O(0.1)$] times ν_a', therefore

$$\nu_a^b = 4.0\times10^{15}\,\mathrm{Hz}\,k\left[\epsilon_{B,-1}^{p/2}\eta_{2.5}^{-4(p+2)}\ \delta t_{-1}^{-(p+8)}L_{52}^{(8+p)/2}\nu_{b,20.1}^{2(p-2)}\right]^{1/(p+12)}. \tag{12}$$

Please note that ν_m^b, ν_c^b and ν_a^b are all measured in the local frame. To translate into the observer frame, all of them need to be multiplied by $1/(1+z)$, $z\sim 1$ being the typical redshift of GRBs. The peak flux can be estimated by

$$\begin{aligned}F_{\nu_a}^b &= F_{\nu_{max}}^b\left(\frac{\nu_m^b}{\nu_c^b}\right)^{-1/2}\left(\frac{\nu_a^b}{\nu_m^b}\right)^{-(p+2)/4}\\ &= 0.144\,\mathrm{Jy}\,\epsilon_{B,-1}^{(p-3)/(p+12)}k^{-(p+2)/4}\left(\frac{1+1/2k_\pm}{1.38}\right)\\ &\quad\times\eta_{2.5}^{2(14-3p)/(p+12)}\delta t_{-1}^{10/(p+12)}L_{52}^{(p+7)/(p+12)}\nu_b^{5(p-2)/(p+12)}\\ &\quad\times\left(\frac{1+z}{2}\right)D_{L,28.34}^{-2},\end{aligned} \tag{13}$$

where $F_{\nu_{max}}^b = N_{rad}^b\eta P_{\nu_m}^b(1+z)/4\pi D_L^2$, $N_{rad}^b = 2N_{e^\pm}(1+\frac{1}{2k_\pm})t_{life}^b/\delta t$, $P_{\nu_m}^b = e^3B^b/m_e c^2$. D_L is the luminosity distance of the source (we take $H_0 = 65$ km s^{-1}MpC^{-1}, $\Omega_m = 0.3$, $\Omega_\wedge = 0.7$).

Since $\nu_c^b < \nu_{R,obs} = 5\times10^{14}$ Hz $< \nu_m^b < \nu_a^b$, the observed R-band flux can be estimated by

$$\begin{aligned}F_{\nu_{R,obs}}^b &= F_{\nu_a}^b\left[\frac{(1+z)\nu_{R,obs}}{\nu_a^b}\right]^{5/2}\\ &= 4.5\,\mathrm{mJy}\,k^{-(p+12)/4}[(1+1/2k_\pm)/1.38]\\ &\quad\times\left(\frac{1+z}{2}\right)^{7/2}D_{L,28.34}^{-2}\epsilon_{B,-1}^{-1/4}L_{52}^{-1/4}\eta_{2.5}^4\,\delta t_{-1}^{5/2},\end{aligned} \tag{14}$$

which hints, for typical parameters, that the optical emission is weak to $m_R\approx 15$.

Similarly, for $\nu_{obs} = 1.8\times10^{15}$ Hz corresponding to a wavelength of $\lambda = 170$ nm, the upper limit of UVOT carried by *Swift* (see in http://swift.gsfc.nasa.gov), the predicted emission is high up to $m\simeq 12$th mag.

Pe'er & Waxman (2003) have calculated the prompt GRB spectra ($>$0.1 keV) in great detail within the fireball model framework, and some important effects such as the $e^\pm$ pairs production/annihilation and so on have been taken into account. In order to estimate the validity of our calculation, we compare our results with their detailed numerical calculations (Pe'er & Waxman 2003), and find that our results do not show much difference from theirs. For example, for their low compactness case shown in their fig. 4: $L = 10^{52}$ erg, $\epsilon_e = \epsilon_B = 10^{-1/2}$, $p = 3$, $\delta t = 0.01$ s and $\eta = 300$. The flux $F_{\nu_{R,obs}}\sim 5\times10^{-5}$ Jy (we have extended their figure to $h\nu_{R,obs}\approx 2$ eV energy range, at which energy band $F_\nu\propto\nu^{5/2}$). With these parameters, our simple analytic result (see equation 14) gives $F_{\nu_{R,obs}}\sim 1.4\times10^{-5}$ Jy. Therefore, as an approximation, we think that our analytic results can be used to estimate the UV/optical emission from GRBs.

Below we discuss the possible SSC (synchrotron self-Compton) radiation briefly. The typical energy of SSC radiation can be estimated by $h\nu_m^{SSC}\simeq 2\gamma_{pair,m}^2h\nu_m\approx 18$ keV. The ratio of the SSC luminosity (L_{SSC}) to the synchrotron luminosity (L_{syn}) of $e^\pm$ pairs can be estimated by $x\equiv L_{SSC}/L_{syn} = [U_e/(1+x)]/U_B^b$, where U_e/U_B^b are the electron/magnetic energy densities, respectively. Hence $x = (-1+\sqrt{1+4U_e/U_B^b})/2 = (-1+\sqrt{1+4E_{\gamma,\nu>\nu_{cut}}/\epsilon_B E_\gamma})/2\sim 0.6$ for $\epsilon_B\simeq 0.1$. $L_{syn}/L\approx E_{\gamma,\nu>\nu_{cut}}/(1+x)E_\gamma\approx(\nu_{cut}/\nu_b)^{(2-p)/2}/(1+x)$. Therefore, $L_{SSC}/L\approx x\,(\nu_{cut}/\nu_b)^{(2-p)/2}/(1+x)\approx 0.04$. So the SSC component can change the observed soft gamma-ray spectrum in some degree, which may help to explain the observed X-ray excess in some GRBs (Band et al. 1993).

3.2 Highly magnetized fireball

For the highly magnetized fireball, the characteristic synchrotron emission frequency of the new born $e^{\pm}$ pairs can be estimated by

$$\nu_{\rm m}^{\rm m} = \eta\gamma_{\rm pair,m}^2 \frac{eB^{\rm m}}{2\pi m_{\rm e}c} \approx 4.4\times10^{15}\,{\rm Hz}\,\epsilon^{\frac{1}{2}}\nu_{\rm b,20.1}^{2(2-p)/p}L_{52}^{(p-8)/2p}\,\delta t_{-1}^{(4-p)/p}\eta_{2.5}^{16/p}. \quad (15)$$

In the present case, we assume that electromagnetic energy dominated over the other ones, thus $B^{\rm m}$ can be estimated by $B^{\rm m} \approx 6.3\times 10^3$ Gauss $\epsilon^{1/2}L_{52}^{1/2}\eta_{2.5}^{-3}\,\delta t_{-1}^{-1}$, $\epsilon = E_{\rm B}/E_\gamma \sim 1$.

Now, the electron with a Lorentz factor $\gamma_{\rm e}$ ($\gg\gamma_{\rm e,c}$) cools down to $\gamma_{\rm e,c}$ at a time-scale

$$t_{\rm life}^{\rm m} \approx 3\pi m_{\rm e}c/\sigma_{\rm T}B^{\rm m2}\eta\gamma_{\rm e,c} \approx 0.016\,{\rm s}\,\epsilon^{-1}L_{52}^{-1}\eta_{2.5}^5\,\delta t_{-1}^2. \quad (16)$$

The characteristic frequency with respect to $\gamma_{\rm e,c}$ is

$$\nu_{\rm c}^{\rm m} = \eta\gamma_{\rm e,c}^2\frac{eB^{\rm m}}{2\pi m_{\rm e}c} \approx 2.1\times10^{13}\,{\rm Hz}\,\epsilon^{1/2}L_{52}^{1/2}\eta_{2.5}^{-2}\,\delta t_{-1}^{-1}. \quad (17)$$

The synchrotron self-absorption frequency ($\nu_{\rm a} > \nu_{\rm m}$) can be estimated by (Wu et al. 2003)

$$\nu_{\rm a}^{\rm m} = 5.6\times10^{15}\,{\rm Hz}\left[\epsilon^{p/2}\eta_{2.5}^{-4(p+2)}\,\delta t_{-1}^{-(p+8)} \times L_{52}^{(8+p)/2}\nu_{\rm b,20.1}^{2(p-2)}\right]^{1/(p+12)}, \quad (18)$$

where it is assumed that the amount of electrons/positrons carried by the fireball is far less than the amount of $e^{\pm}$ pairs generated in the gamma-ray phase (Zhang & Mészáros 2002). Now the peak flux can be estimated by

$$F_{\nu_{\rm a}}^{\rm m} = F_{\nu_{\rm max}}^{\rm m}\left(\frac{\nu_{\rm m}^{\rm m}}{\nu_{\rm c}^{\rm m}}\right)^{-1/2}\left(\frac{\nu_{\rm a}^{\rm m}}{\nu_{\rm m}^{\rm m}}\right)^{-(p+2)/4} = 0.096\,{\rm Jy}\,\epsilon^{(p-3)/(p+12)}\eta_{2.5}^{2(14-3p)/(p+12)}\,\delta t_{-1}^{10/(p+12)} \times L_{52}^{(p+7)/(p+12)}\nu_{\rm b}^{5(p-2)/(p+12)}\left(\frac{1+z}{2}\right)D_{\rm L,28.34}^{-2}, \quad (19)$$

where $F_{\nu_{\rm max}}^{\rm m} = N_{\rm rad}^{\rm m}\,\eta\,P_{\nu_{\rm m}}^{\rm m}(1+z)/4\pi\,D_{\rm L}^2$, $N_{\rm m}^{\rm rad} = 2N_{\rm e^{\pm}}t_{\rm life}^{\rm m}/\delta t$, $P_{\nu^{\rm m}}^{\rm m} = e^3B^{\rm m}/m_{\rm e}c^2$.

The observed R-band flux can be estimated by

$$F_{\nu_{R,\rm obs}}^{\rm m} = F_{\nu_{\rm a}}^{\rm m}\left[\frac{(1+z)\nu_{R,\rm obs}}{\nu_{\rm a}^{\rm m}}\right]^{5/2} = 1.4\,{\rm mJy}\left(\frac{1+z}{2}\right)^{7/2}D_{\rm L,28.34}^{-2}\epsilon^{-1/4}L_{52}^{-1/4}\eta_{2.5}^4\,\delta t_{-1}^{5/2}, \quad (20)$$

which hints, for typical parameters, that the optical emission is weak to $m_R \approx 16$.

Similarly, for $\nu_{\rm obs} = 1.8\times10^{15}$ Hz, the predicted emission is up to $m \simeq 13$th mag.

In the present case, the typical energy of the SSC radiation can be estimated by $h\nu_{\rm m}^{\rm SSC} \simeq 2\gamma_{\rm pair,m}^2\,h\nu_{\rm m} \approx 35$ keV. Now, $x = (-1+\sqrt{1+4U_{\rm e}/U_{\rm B}^{\rm m}})/2 = (-1+\sqrt{1+4E_{\gamma,\nu>\nu_{\rm cut}}/\epsilon E_\gamma})/2 \approx E_{\gamma,\nu>\nu_{\rm cut}}/\epsilon E_\gamma$ for $E_{\gamma,\nu>\nu_{\rm cut}} \in E_\gamma$. Thus $L_{\rm SSC}/L \approx 1/[(1+x)\epsilon(\nu_{\rm cut}/\nu_{\rm b})^{(p-2)}] \approx 0.01\epsilon^{-1}$, which implies that the SSC component cannot change the observed soft gamma-ray spectrum significantly, at least for the typical parameters taken here.

4 DISCUSSION AND CONCLUSIONS

GRBs are characterized by emission in a few hundred keV ranges with a non-thermal spectrum, X-ray emission is weaker, where only a few per cent of the energy is emitted below 10 keV and prompt emission at lower energies has not been observed so far. One exception is the optical flash accompanying GRB 990123 (Akerlof et al. 1999), which is believed to be powered by the reverse shock (Sari & Piran 1999). If such an emission is the low-energy tail of the gamma-ray emission, the light curves in the different energy bands should be highly correlated, which is not the case (Sari & Piran 1999). Akerlof et al. (2000) have performed a search for optical counterparts to six GRBs with location errors of 1 deg^2 or better, but no optical counterpart has been detected, the earliest limiting sensitivity is $m > 13.1$ at 10.85 s after the gamma-ray rises. Neither has any simultaneous optical emission from GRBs been detected by Kehoe et al. (2001). All of these observations suggest that the simultaneous optical emission should not be typically brighter than 14 mag, which coincides with our results presented here.

The typical prompt optical emission predicted in this paper, $m_R \sim$ 15–16 mag, is significantly stronger than $m_\nu \sim 18$ mag predicted by Katz (1994). Such emission can be detected by the current ROTSE-IIIa telescope system, which is a 0.45-m robotic reflecting telescope and managed by a fully automated system of interacting daemons within a Linux environment. The telescope has an f-ratio of 1.9, yielding a field of view of 1.8×1.8 deg^2. The control system is connected via a TCP/IP socket to the Gamma-ray Burst Coordinate Network (GCN), which can respond to GRB alerts fast enough (<10 s). ROSTE-IIIa can reach 17 mag in a 5-s exposure, 17.5 in 20-s exposure (see Smith et al. 2003 for detail), which is sufficient to detect the optical emission predicted in this paper. However, for the standard fireball model, the very early optical emission powered by the reverse shock can be up to $m_R \sim 9$ mag or even brighter (Sari & Piran 1999; Li et al. 2003; Wu et al. 2003), which far surpasses the optical emissions predicted here. In practice, such strong early optical emission should be very rare, since it has not been detected for most GRBs (Akerlof et al. 2000; Kehoe et al. 2001). It is unclear why the early optical emission is so weak. If the fireball is highly magnetized, such emission may be weak to $m_R \sim 14$ mag at the deceleration radius $R_{\rm dec} \sim 10^{17}$ cm, the corresponding time-scale $t_{\rm obs} \sim 20$ s $(1+z)R_{\rm dec,17}\eta_{2.5}^{-2}$ (Fan, Wei & Wang 2004b). In the collision model of the magnetized wind and the external medium proposed by (Smolsky & Usov 2000), the synchrotron radiation generated in the vicinity of the wind front can be high, up to tens of MeV, rather than eV as we generally suggest. In this case, the very early optical afterglow is very weak. So, the optical emission accompanying the GRB may be detected independently.

As a result of the strong synchrotron self-absorption, the emission peaks at the UV band. For $\nu_{\rm obs} = 1.8\times10^{15}$ Hz ($\lambda = 170$ nm), the typically simultaneous emission is high, up to $m \simeq$ 12–13 mag, which is bright enough to be detected by the UVOT (covering 170–650 nm with six colours) carried by *Swift*, planned for launch in early 2004. The observation of that UV emission is important, since: at the UV band, the spectrum predicted in this paper takes the form of $F_\nu \propto \nu^{5/2}$, which is significantly different from that of the reverse shock emission, $F_\nu \propto \nu^{-\beta/2}$, where $\beta \simeq 2.2$ is the index of the power-law distribution of the relativistic electrons heated by the reverse shock (Sari & Piran 1999; Fan et al. 2002; Wu et al. 2003). The flux of UV emission predicted here is far above that of the optical emission, in contrast to the reverse shock emission. Therefore, the spectrum feature at the optical–UV band ($F_\nu \propto \nu^{5/2}$) is a signature of the emission accompanying GRBs.

For both the baryon-rich fireball and the highly magnetized one, the generated $e^{\pm}$ pairs dominate over the electrons (including positrons) associated with the fireball. To reproduce the observed gamma-ray emission, the magnetic field strengths of these two types of fireball are comparable. Consequently, the UV/optical emission predicted here does not show much difference for these two kinds of fireball. However, for the highly magnetized fireball, the magnetic field is ordered, so a high linear polarization of the synchrotron radiation at multiwavelength bands is expected.

Pilla & Loeb (1998) have discussed the possible IC scattering of the resulting $e^{\pm}$ pairs with intrinsic GRB photons, and found that if $U_{\gamma} \gg U_{\rm m}$, the pairs transfer nearly all of their energy back to the radiation field via IC scattering. Fortunately, for the two cases discussed here, U_{γ} and $U_{\rm m}$ are comparable, so that the IC process may be important, but it is not dominant, especially for the highly magnetized fireball. Therefore, it will not change our result presented here significantly (detailed numerical research is beyond the scope of this paper).

It should be noted that in this paper our results are based on a simple analytic analysis, which is a great simplification of the real situation. In our calculation, some important effects such as pair annihilation have not been taken into account. However, as described in the previous section, we found that our results are not very different from those of detailed numerical calculations (e.g. Pilla & Loeb 1998; Pe'er & Waxman 2003). This suggests that as an order estimation, our present work is reliable. Furthermore, our work has the benefit of showing the scalings with parameters better. We have shown that the predicted flux in the UV/optical band accompanying GRBs strongly depends on the typical variability time-scale (δt) and the typical bulk Lorentz factor (η), i.e. $F \propto \eta^4 \delta t^{5/2}$. In our calculation, we take the value $\delta t \sim 0.1$ s based on the analysis of the BATSE bursts (Shen & Song 2003). In many other works, δt is assumed to be low, in the millisecond range or even shorter. If this is the case, then the UV/optical emission predicted here will be much dimmer unless the Lorentz factor is much larger. Therefore, the further the UVOT observation can provide the better the chances of testing our predictions or imposing some important constraints on the poorly known parameters of GRBs.

ACKNOWLEDGMENTS

YZF thanks Drs D. Guetta, Z. Li and X. F. Wu for their kind help. We also thank T. Lu, Z. G. Dai, Y. F. Huang and X. Y. Wang for valuable comments. We appreciate the anonymous referees for their useful suggestions that enabled us to improve the paper significantly. This work was supported by the National Natural Science Foundation of China (grants 10073022, 10225314 and 10233010) and the National 973 Project (NKBRSF G19990754).

REFERENCES

Akerlof C. et al., 1999, Nat, 398, 400
Akerlof C. et al., 2000, ApJ, 532, L25
Band D. et al., 1993, ApJ, 413, 281
Cheng K.S., Lu T., 2001, Chin. J. Astron. Astrophys., 1, 1
Coburn W., Boggs S.E., 2003, Nat, 423, 415
Dai Z.G., Lu T., 2002, ApJ, 580, 1013
Fan Y.Z., Dai Z.G., Huang Y.F., Lu T., 2002, Chin. J. Astron. Astrophys., 2, 449
Fan Y.Z., Dai Z.G., Lu T., 2004a, Acta Astron. Sinica, 45, 25
Fan Y.Z., Wei D.M., Wang C.F., 2004b, ApJ, submitted
Fishman G.J., Meegan C.A., 1995, ARA&A, 33, 415
González M.M., Dingus B.L., Kaneko Y., Preece R.D., Dermer C.D., Briggs M.S., 2003, Nat, 424, 14
Guetta D., Granot J., 2003, ApJ, 585, 885
Guetta D., Spada M., Waxman E., 2001, ApJ, 557, 399
Katz J.Z., 1994, ApJ, 432, L107
Kehoe R. et al., 2001, ApJ, 554, L159
Li Z., Dai Z.G., Lu T., Song L.M., 2003, ApJ, 599, 380
Lithwick Y., Sari R., 2001, ApJ, 555, 540
Lyutikov M., Pariev V.I., Blndford R.D., 2003, ApJ, 597, 998
Mészáros P., 2002, ARA&A, 40, 137
Mészáros P., Rees M.J., 1997, ApJ, 482, L29
Mészáros P., Ramirez-Ruiz E., Rees M.J., Zhang B., 2002, ApJ, 578, 812
Paczyński B., Xu G.H., 1994, ApJ, 427, 708
Pe'er A., Waxman E., 2003, ApJ, submitted (astro-ph/0311252)
Pilla R., Loeb A., 1998, ApJ, 494, L167
Rees M.J., Mészáros P., 1994, ApJ, 430, L93
Sari R., Piran T., 1999, ApJ, 517, L109
Schaefer B.E. et al., 1994, ApJ, 422, L71
Schaefer B.E. et al., 1998, ApJ, 492, 696
Shaviv N.J., Dar A., 1995, ApJ, 447, 863
Shen R.F., Song L.M., 2003, PASJ, 55, 345
Smith D. et al., 2003, A&AS, 202, 4602
Smolsky M.V., Usov V.V., 2000, ApJ, 537, 764
Thompson C., 1994, MNRAS, 270, 480
Usov V.V., 1994, MNRAS, 267, 1035
Waxman E., 2003, Nat, 423, 388
Wei D.M., Cheng K.S., 1997, MNRAS, 290, 107
Wu X.F., Dai Z.G., Huang Y.F., Lu T., 2003, MNRAS, 432, 1131
Zhang B., Mészáros P., 2002, ApJ, 581, 1236
Zhang B., Mészáros P., 2003, Int. J. Mod. Phys. A, in press (astro-ph/0311321)
Zhang B., Kobayashi S., Mészáros P., 2003, ApJ, 595, 950

This paper has been typeset from a TEX/LATEX file prepared by the author.